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Effects of loading rate on root pullout performance of two plants in the eastern Loess Plateau, China

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Abstract: Root pullout performance of plants is an important mechanical basis for soil reinforcement by plant roots in the semi-arid areas. Studies have shown that it is affected by plant factors (species, ages, root geometry, etc.) and soil factors (soil types, soil moisture, soil bulk densities, etc.). However, the effects of loading rates on root pullout performance are not well studied. To explore the mechanical interactions under different loading rates, we conducted pullout tests on *Medicago sativa* L. and *Hippophae rhamnoides* L. roots under five loading rates, i.e., 5, 50, 100, 150, and 200 mm/min. In addition, tensile tests were conducted on the roots in diameters of 0.5–2.0 mm to compare the relationship between root tensile properties and root pullout properties. Results showed that two root failure modes, slippage and breakage, were observed during root pullout tests. All *M. sativa* roots were pulled out, while 72.2% of *H. rhamnoides* roots were broken. The maximum fracture diameter and fracture root length of *H. rhamnoides* were 1.22 mm and 7.44 cm under 100 mm/min loading rate, respectively. Root displacement values were 4.63% (±0.43%) and 8.91% (±0.52%) of the total root length for *M. sativa* and *H. rhamnoides*, respectively. The values of maximum pullout force were 14.6 (±0.7) and 17.7 (±1.8) N under 100 mm/min for *M. sativa* and *H. rhamnoides*, respectively. Values of the maximum pullout strength for *M. sativa* and *H. rhamnoides* were 38.38 (±5.48) MPa under 150 mm/min and 12.47 (±1.43) MPa under 100 mm/min, respectively. Root-soil friction coefficient under 100 mm/min was significantly larger than those under other loading rates for both the two species. Values of the maximum root pullout energy for *M. sativa* and *H. rhamnoides* were 87.83 (±21.55) mm•N under 100 mm/min and 173.53 (±38.53) mm•N under 200 mm/min, respectively. Root pullout force was significantly related to root diameter (P<0.01). Peak root pullout force was significantly affected by loading rates when the effect of root diameter was included (P<0.01), and vice versa. Except for the failure mode and peak pullout force, other pullout parameters, including root pullout strength, root displacement, root-soil friction coefficient, and root pullout energy were not significantly affected by loading rates (P>0.05). Root pullout strength was greater than root tensile strength for the two species. The results suggested that there was no need to deliberately control loading rate in root pullout tests in the semi-arid soil, and root pullout force and pullout strength could be better parameters for root reinforcement model compared with root tensile strength as root pullout force and pullout strength could more realistically reflect the working state of roots in the semi-arid soil.

Keywords: plant roots; soil reinforcement; loading rate; root pullout properties; root-soil interaction; loess area

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1 Introduction

Exposed to water, wind, and other external forces, soil slopes are susceptible to erosion and unstable events. Soil erosion has become one of the most serious eco-environmental problems in China and other countries. Soil erosion in the arid and semi-arid areas on the Chinese Loess Plateau is very prominent. It is becoming increasingly popular to control soil erosion and protect unstable slopes with vegetation (Mickovski and Ennos, 2003; De Baets et al., 2006; Peng and Lin, 2013). The beneficial hydrological effects of vegetation on slope protection mainly include the interception of rainfall, the reduction of splash erosion by raindrops, and the control of surface runoff (Ruan et al., 2022; Simon and Collison, 2002). Besides, plant roots can mechanically reinforce soil and improve slope stability (De Baets et al., 2008; Cislaghi et al., 2021; Spiekermann et al., 2021).

The mechanical effects of plant roots on soil consist of the reinforcement of shallow soil by fine and shallow roots (Wang et al., 2015), the anchorage by coarse and deep roots (Reubens et al., 2007; Stubbs et al., 2019), and the traction by lateral roots (Abdi et al., 2009; Zhang et al., 2014). The strengthening effect of roots on soil is primarily due to friction at the root-soil interface and root anchorage against soil shear deformation. In shallow soil, root system strengthens soil through the complex mechanical interactions between roots and soil to enhance soil shear strength (Operstein and Frydman, 2000; Pollen and Simon, 2005). Under certain stress conditions, root system would start to slip out of soil or have a tendency to slip. Friction against slippage is then generated at the root-soil interface, which combines root tensile strength with soil shear strength and improves the strength of root-soil composite (Cohen et al., 2011; Fan and Tsai, 2016; Yildiz et al., 2018).

Due to the complexity of plant root structure and root-soil interaction, it is difficult to quantify the ability of roots to reinforce soil and stabilize slopes. The existing comprehensive models of root reinforcement generally take into account root geometry, root mechanical properties, and root-soil mechanical interactions (Dupuy et al., 2005; Schwarz et al., 2010a). As one of the most important parameters of root mechanical properties, root tensile strength has been widely studied (Leung et al., 2015; Giadrossich et al., 2016; Zhang et al., 2019). The studies have focused on the measurement of root tensile strength, the exploration of root failure mechanism, and the quantification of root-soil interaction (Abernethy and Rutherfurd, 2001; Mickovski et al., 2007). Root pullout properties, aiming for the presentation of root-soil interaction, have also been much explored. The existing researches have showed that root pullout force is affected by root length, root branching pattern, root curvature, and soil moisture content (Mattia et al., 2005; Stokes et al., 2009; Mickovski et al., 2010; Zhang et al., 2020a). Root-soil friction coefficient largely depends on soil type and soil water content (Schwarz et al., 2010a).

The action of root-soil friction results in different failure modes of roots in root pullout tests. For example, small roots are easy to break under dry conditions but slip out under wet conditions in cohesive soils (Pollen, 2007; Schwarz et al., 2011). When pullout force on roots exceeds the maximum static friction between roots and soil, the roots tend to slide gradually. The friction then changes from static friction to sliding friction (Schwarz et al., 2010a). Roots are likely to be broken when root pullout force is greater than the maximum root tensile force, or be pulled out when root pullout force is smaller than the maximum root tensile force (Leung et al., 2018). Many researchers have studied the factors that affect root pullout characteristics, such as root diameter, root length, root bifurcation, and soil moisture content (Osman et al., 2011). However, most of them only focus on the effect of the factors on peak pullout force. For example, peak pullout force of plant roots increases with root diameter, root length, and the number of lateral roots (Schwarz et al., 2010b; Ji et al., 2018). Under certain conditions, root pullout force decreases with soil water content in a power function (Zhang et al., 2020b). However, few studies focused to root pullout energy, which can be used to show the ability of root system to resist external forces during root pulling process, and can reflect the reinforcing effect of root system on soil shear strength from the perspective of energy.

Ability of plant roots to protect slopes varies with plant species. And performance of root-soil interactions of different plant roots can be evaluated by root pullout tests. Roots of *in situ* pullout tests can be exposed by trenches dug around plants (Norris, 2005; Vergani et al., 2016), or exposed by high-pressure water/air (Marden et al., 2005; Giadrossich et al., 2017). Various chucks and stretching devices are used to pull out roots (Abernethy and Rutherfurd, 2001; Docker and Hubble, 2008; Schwarz et al., 2011). Nevertheless, almost no device can control the loading rate of root pulling except for the device used by Schwarz et al. (2011), and no result is reported about the specific effect of loading rate on root reinforcement. In reality, plant roots are subjected to complex loads including runoff and wind. The landslide or failure of slopes triggered by rainfall and/or wind generally occurs in the rate range from 1 to 300 mm/min (Liu and Shih, 2013; Hungr et al., 2014; Iverson et al., 2015). Root tensile properties are affected by loading rates. The existing researches have showed that plant roots stretched at larger tensile rates show greater root tensile strengths (Cofie and Koolen, 2001; Zhang et al., 2012), and roots could be easier to be broken under larger loading rates (Ji et al., 2018). However, there is a lack of in-depth research on the effect of loading rate on root-soil interaction, which could limit the smooth and accurate conduct of root pullout tests. Therefore, the aims of this study were: (1) to investigate how loading rates affect root pullout properties, including the maximum displacement, peak pullout force, root-soil friction coefficient, and root pullout energy; (2) to discuss root failure modes, the fracture root length, and diameter of pulled roots under different loading rates; and (3) to suggest a suitable loading rate for root pullout tests in the semi-arid area. This study can provide a reference for a better understanding of the effects of test method on the measurement of root-soil interaction, and provide support for the evaluation of soil reinforcement by plant roots.

2 Materials and methods

2.1 Study area

This study was carried out in the Taiyuan City (37°27′–38°25′N, 111°30′–113°09′E), which is located in the eastern Loess Plateau of China with an annual average temperature of 9.5°C. Monthly average temperatures range from –6.4°C in January to 23.0°C in July. The altitude ranges from 760 to 2670 m a.s.l., having an average value of approximate 800 m a.s.l. The study area belongs to a typical continental climate with relatively dry air and less precipitation. The annual precipitation is 468.4 mm, and the average annual evaporation is 1644.9 mm. The precipitation is mainly concentrated in June to August.

2.2 Preparation of samples

Soil used in the experiment was taken from Juewei Mountain in the northwest of the Taiyuan City. After air-dried, and crushed in the laboratory, it was sieved with a 3-mm sieve for preparation. The soil was a sandy loam. Roots of *Medicago sativa* L. and *Hippophae rhamnoides* L. were collected from cultured plants in the cultivation boxes having a dimension of 50 cm×50 cm×50 cm with the soil. *M. sativa* is a perennial herbaceous plant, and *H. rhamnoides* is a deciduous shrub. Due to the strong resistance to low temperature and drought, they are widely planted, and become pioneer plants for ecological, water, and soil conservation on the arid and semi-arid areas of the Loess Plateau, China. We put boxes in natural environment and watered 0–2 times weekly according to the rainfall condition. Grown for 4 months, the roots were excavated with water flushing method. Healthy and intact root samples were selected and trimmed to a length of 16.0 cm for root pullout tests and tensile tests. Root diameter was measured using a digital vernier caliper with an accuracy of 0.03 mm. Roots were marked every 40 mm and measured 3 times per marked position to obtain the average root diameter. They were stored in a refrigerator at 4°C to maintain root freshness.

Remolded soil samples embedding the roots were prepared for root pullout tests (Fig. 1). The above sandy loam was filled and compacted in five layers in cubic iron test chambers (200 mm× 200 mm×200 mm) at the soil density of 1.45 g/cm^3 (*M. sativa*) and 1.43 g/cm^3 (*H. rhamnoides*)

using the WDW-5 electronic universal testing system (UTS, Changzhou Sanfeng Instrument Technology Co., Ltd., Changzhou, China). The boxes had two removable plates, one of which had a narrow gap (60 mm×10 mm) in the center for exposing the roots. Compaction speed was 50 mm/min. During the compaction, two 16.0 cm-length roots (free length 4.0 cm+buried length 12.0 cm) were placed into the narrow gap of each box vertically (root burial angle 90°) in a spacing of 60 mm when the soil was loaded to the second layer. The surface of preceding soil layer was roughened before each new soil layer was added. Soil water content of the remolded samples was 9.74% (*M. sativa*) and 8.44% (*H. rhamnoides*) determined by the oven-dry method. In the study, diameter ranges of *M. sativa* and *H. rhamnoides* were 0.5–1.0 and 0.8–2.0 mm, respectively. Remolded samples were stood for 24 h at 4°C before root pullout tests to ensure firm bonds between roots and soil.

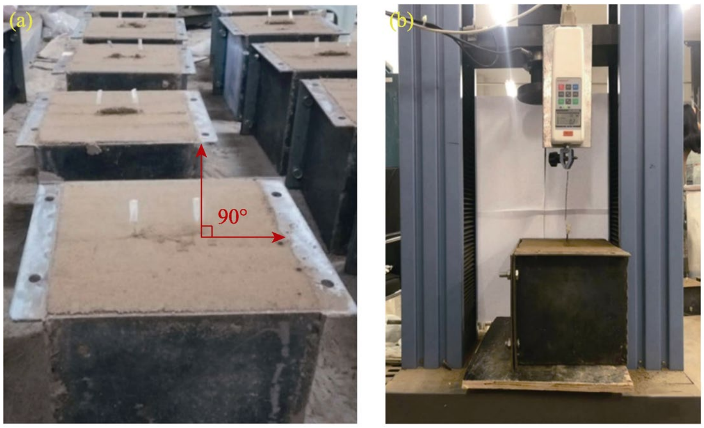

Fig. 1 Pullout tests were conducted on roots embedded in remolded samples. (a), remolded samples; (b), root pullout test.

2.3 Root pullout tests

Root pullout tests were conducted on the remolded soil samples by WDW-5 UTS connected with SH-200 digital force gauge (SUNDOO, Foshan Zhunce Electronics Co., Ltd., Foshan, China). Totally 44 roots of *M. sativa* and 43 roots of *H. rhamnoides* were tested. A 20 mm-wide medical tape was wrapped around the free end of the roots to prevent root slippage or breakage during the pulling process of root pullout tests. Free end of the roots in remolded samples was firstly fixed in the clamp of force gauge. After setting the reading of force gauge to zero, root was then pulled unfrt a setting load rate (Fig. 1b). Five loading rates, i.e., 5, 50, 100, 150, and 200 mm/min, were used in this study. They were all within the landslide rate range, which can be used to reflect the performance of root system in landslides. After root was completely pulled out or broken, data including peak pullout force, fracture root diameter, fracture root length, and force-displacement curve were recorded and saved. Fracture root length was the distance between upper clamp and fracture point. Fracture root diameter was the average value of root diameter at a distance of 10 mm near fracture point of two fractured root segments after fracture. Root displacement was the change in position of root from its initial position in soil to its final failure position. Parameters of root pullout properties including pullout strength (P_R; MPa) and root-soil interface friction coefficient (μ; Xie, 1990) were calculated as follows:

$$P_R = \frac{4F_P}{\pi D^2}, \tag{1}$$

where F_P is the peak root pullout force (N); and D is the average root diameter (mm).

$$\mu = \frac{2F_p \cos(1-\theta)}{\gamma_s \pi D L^2}, \tag{2}$$

where γ_s is the soil bulk density (g/cm^3); L is the root burial depth (cm); and θ is the root burial angle (rad).

Root pullout energy (V_ε; mm·N) is the work done by external force when the peak pullout force reaches, which is:

$$V_\varepsilon = \int_0^x F(x)dx , \tag{3}$$

where $F(x)$ is the curvilinear relationship between pullout force and displacement before peak pullout force; x is the displacement before the peak pullout force (N); and d is the root diameter (mm). Root pullout energy can be used to show the ability of root system to resist external forces during root pulling process, and can reflect the reinforcing effect of root system on soil shear strength from the perspective of energy.

2.4 Root tensile tests

The purpose of root tensile tests was to estimate the strength of individual roots, and then to compare it with the strength of root pullout tests. Roots selected for the tensile tests had similar diameters as those in the root pullout rests. Root tensile tests were conducted on 16.0 cm-length roots of the two species using WDW-5 UTS. In order to decrease rupture and slippage at clamping position, we struck 20 mm-wide medical tapes at each end of the roots before tests. Stretching speed was 100 mm/min. The peak tensile force and corresponding root deformation of each test were measured and recorded. Only the data of roots broken away from clamps were regarded as valid data. Totally, 21 roots of *M. sativa* and 37 roots of *H. rhamnoides* were successfully tested. Root tensile strength (T_R; MPa) was calculated by the following formula:

$$T_R = \frac{4F_T}{\pi D^2}, \tag{4}$$

where F_T is the peak root tensile force (N).

Root elastic modulus (E; MPa) was calculated by the following formula:

$$E = \frac{T_R}{\varepsilon}, \tag{5}$$

where ε is the root elongation (%), which is equal to root deformation at root failure divided by root original gauge length (160 mm).

2.5 Data analysis

Data were analyzed by SPSS 2020. One-way analysis of variance (ANOVA) was used to evaluate the influence of species and loading rates on fracture diameter, fracture length, displacement, root-soil friction coefficient, peak pullout force and strength, and pullout energy of roots. Analysis of covariance (ANCOVA) was used to analyze the differences in pullout performance of roots under different loading rates. Significant influence of loading rates and species on root pullout properties was tested at $P<0.05$ level. Correlation analysis was carried out on the pullout properties and affecting factors, loading rate, and root diameter. Graphs were plotted using OriginPro 2016.

3 Results

3.1 Fracture root diameter and fracture root length

In the study, 39 roots of *M. sativa* and 36 roots of *H. rhamnoides* were successfully tested. No significant difference in root diameter existed between tested samples under different loading rates (Table 1). All *M. sativa* roots were in slippage failure, while 26 *H. rhamnoides* roots were in breakage failure. It indicates that the failure mode of *M. sativa* roots is mainly sliding failure, and that of *H. rhamnoides* roots is mainly breakage failure. Most slippage failure of *H. rhamnoides* roots occurred under 100 mm/min loading rate.

Table 1 Root diameters of different species used in the pullout tests

Species	Loading rate (mm/min)	Number of roots successfully tested	Average root diameter (mm)
Medicago sativa L.	5	8	0.72±0.06[a]
	50	7	0.74±0.04[a]
	100	9	0.72±0.05[a]
	150	8	0.71±0.06[a]
	200	7	0.72±0.02[a]
Hippophae rhamnoides L.	5	6	1.35±0.13[a]
	50	6	1.37±0.13[a]
	100	12	1.37±0.09[a]
	150	6	1.41±0.15[a]
	200	6	1.40±0.16[a]

Note: Different lowercase letters within the same column indicate significant differences among different loading rates at $P<0.05$ level. Mean±SD.

Fracture root diameter of *H. rhamnoides* did not change significantly among different loading rates (Fig. 2). Fracture root length under 150 mm/min loading rate was significantly smaller than that under 100 mm/min loading rate (Fig. 2b). The maximum fracture diameter and fracture length were 1.22 mm and 7.44 cm, respectively, which were both observed under 100 mm/min loading rate.

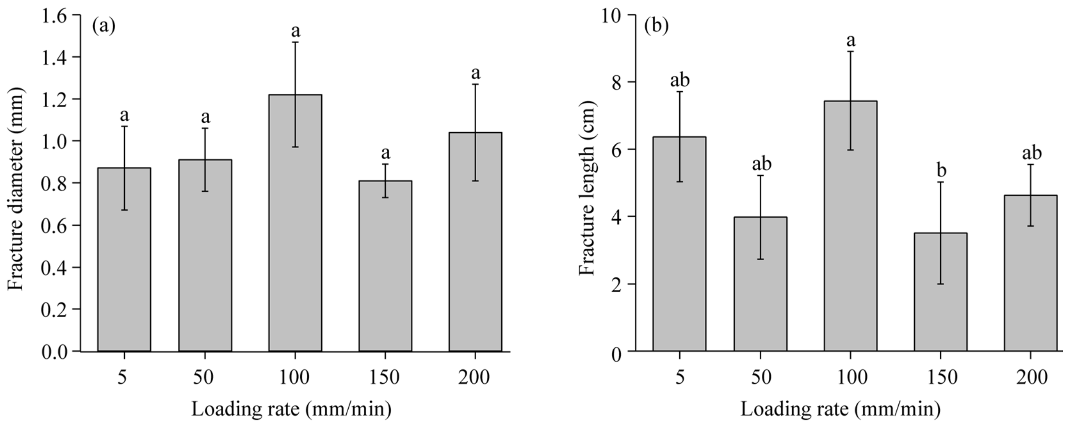

Fig. 2 Fracture diameter (a) and fracture length (b) of *Hippophae rhamnoides* roots under different loading rates. Different lowercase letters indicate significant differences among different loading rates at $P<0.05$ level. Bars are standard errors.

3.2 Root displacement

Difference in root displacement at peak pullout force was not significant among different loading rates. Root displacement was 4.63% (±0.43%) and 8.91% (±0.52%) of the total root length for *M. sativa* and *H. rhamnoides*, respectively. Root displacement of *H. rhamnoides* was about twice that of *M. sativa* (Fig. 3). It could be mainly attributed to the large differences in root displacement due to the different root diameters of the two plants.

3.3 Peak root pullout force and root pullout strength

Peak root pullout force was increased from 5 to 100 mm/min and then decreased from 100 to 200 mm/min for both *M. sativa* and *H. rhamnoides*. The values of maximum pullout force were 14.58 (±0.72) and 17.68 (±1.82) N under 100 mm/min loading rate for *M. sativa* and *H. rhamnoides*, respectively. Peak pullout force of *H. rhamnoides* was 12.20 (±5.40) N, which was greater than that of *M. sativa*. Significant difference in peak pullout force was only observed under 5 mm/min

loading rate for *M. sativa*, while no significant difference in peak pullout force was observed among different loading rates for *H. rhamnoides* (Fig. 4). The peak pullout force of *H. rhamnoides* was increased over that of *M. sativa* under all loading rates except the loading rate of 150 mm/min.

Root pullout strength was varied with loading rate for both *M. sativa* and *H. rhamnoides* (Fig. 4b). The maximum pullout strength was 38.38 (±5.48) MPa for *M. sativa* under 150 mm/min loading rate, and 12.47 (±1.43) MPa for *H. rhamnoides* under 100 mm/min loading rate. Root pullout strength of *M. sativa* was significantly greater than that of *H. rhamnoides*.

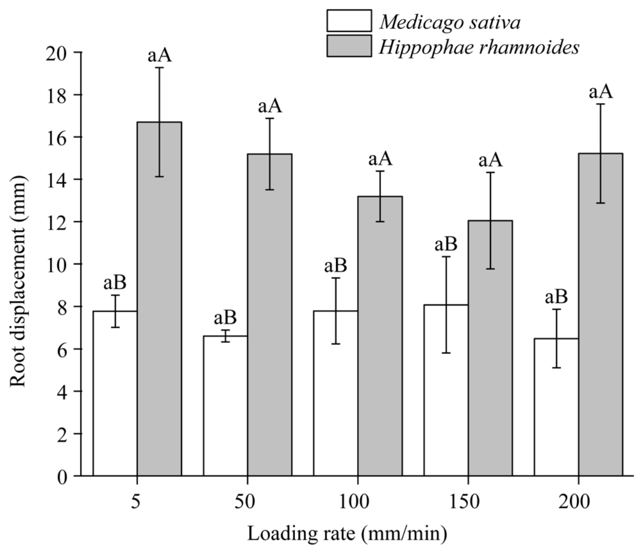

Fig. 3 Root displacement of *Medicago sativa* and *Hippophae rhamnoides* under different loading rates. Different lowercase letters indicate significant differences among different loading rates at $P<0.05$ level. Different uppercase letters indicate significant differences between two species at $P<0.05$ level. Bars are standard errors.

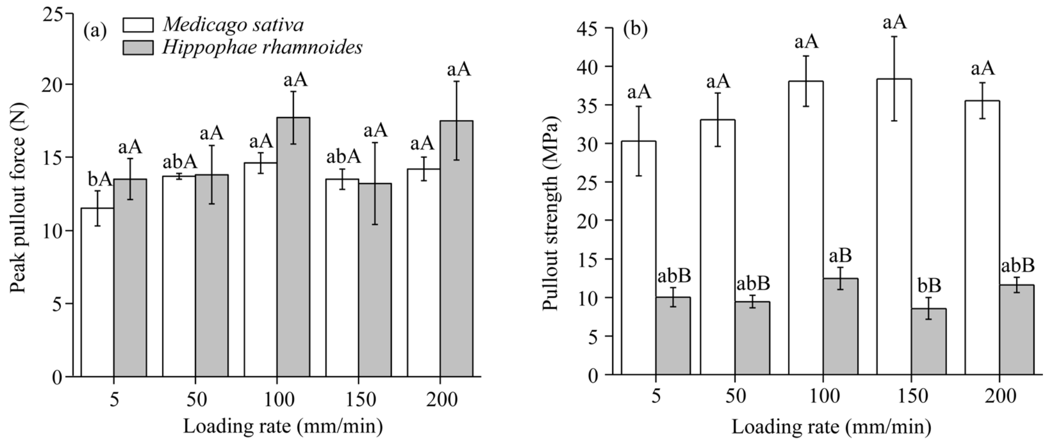

Fig. 4 Root peak pullout forces (a) and strengths (b) of *Medicago sativa* and *Hippophae rhamnoides* under different loading rates. Different uppercase letters indicate significant differences between two species at $P<0.05$ level; Different lowercase letters indicate significant differences between loading rates at $P<0.05$ level. Bars are standard errors.

For *H. rhamnoides*, root slippage force and breakage force increased with root diameter in power functions (Fig. 5), and root pullout strength decreased with root diameter in power functions (Fig. 5b). Peak root pullout force and root pullout strength of slippage roots were greater than those of breakage roots. This was primarily due to the difference between sliding failure and breakage failure mechanism of root system.

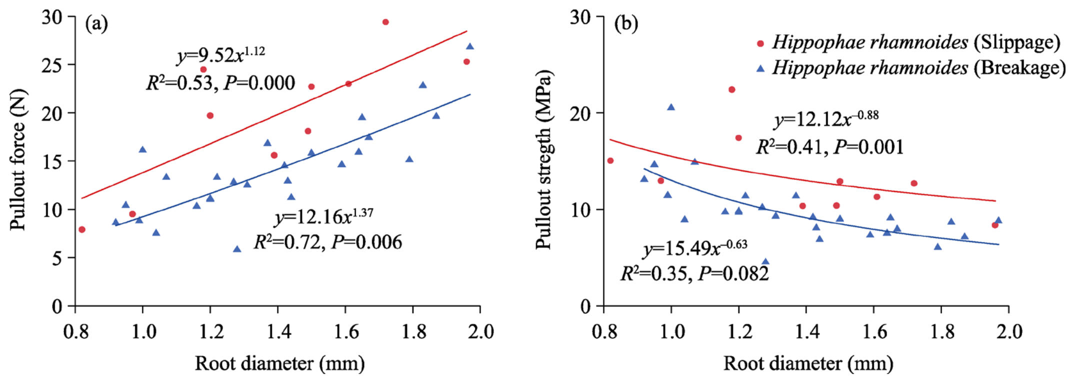

Fig. 5 Correlation of root pullout force (a) and root pullout strength (b) of *Hippophae rhamnoides* roots in breakage and slippage failure with root diameter

3.4 Root-soil friction coefficient

Root-soil friction coefficient of *M. sativa* and *H. rhamnoides* was increased from 5 to 100 mm/min loading rate and then decreased from 100 to 200 mm/min loading rate. Root-soil friction coefficient under 100 mm/min loading rate was significantly larger than those at other loading rates for both the two species (Fig. 6). Root-soil friction coefficient was significantly different among different loading rates for *M. sativa*, but it was not significantly different among different loading rates for *H. rhamnoides*. *M. sativa* had significantly greater root-soil friction coefficient than *H. rhamnoides*.

3.5 Root pullout energy

Root pullout energy of *M. sativa* and *H. rhamnoides* did not change significantly with loading rate (Fig. 6b). The maximum root pullout energy of *M. sativa* and *H. rhamnoides* was 87.83 (±21.55) mm·N under 100 mm/min loading rate and 173.53 (±38.53) mm·N under 200 mm/min loading rate, respectively. *H. rhamnoides* had significantly greater root pullout energy than *M. sativa*.

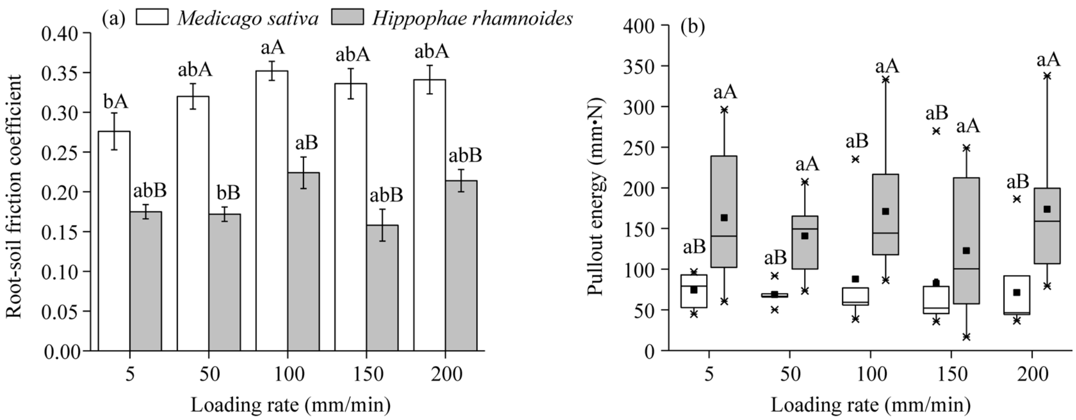

Fig. 6 Root-soil friction coefficients (a) and root pullout energy (b) of *Medicago sativa* and *Hippophae rhamnoides* under different loading rates. Different lowercase letters indicate significant differences between loading rates at P<0.05 level. Different uppercase letters indicate significant differences between species at P<0.05 level. Bars are standard errors. Boxes in figure 6b indicate the IQR (interquartile range, 75th to 25th of the data). The median value is shown as a line within the box. Black square is shown as mean. Whiskers extend to the most extreme value within 1.5×IQR.

3.6 Root tensile properties

Root tensile properties were significantly different between root diameter classes (P<0.05; Fig. 7). For both species, root tensile force increased while root tensile strength and elastic modulus decreased with root diameter (Fig. 7). *M. sativa* showed higher root tensile properties than *H. rhamnoides*.

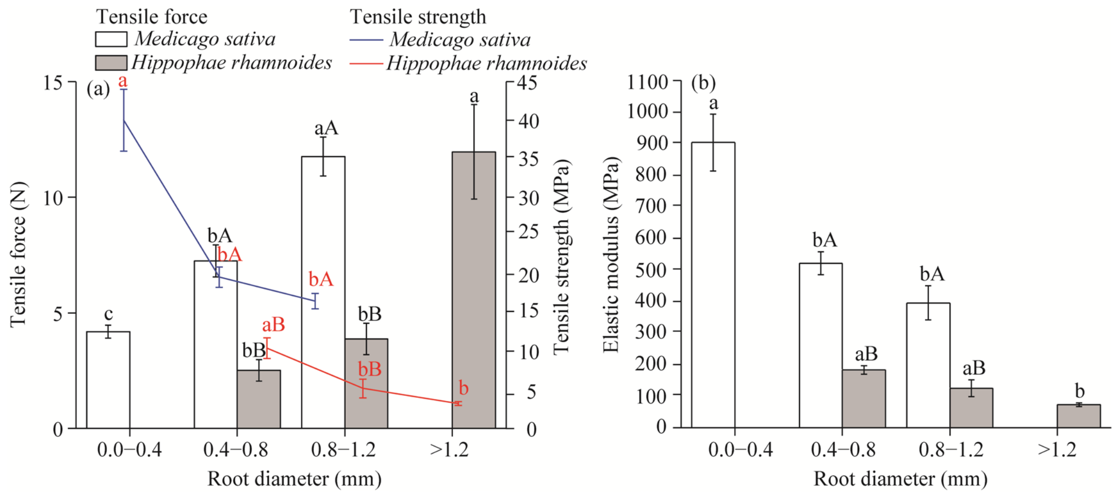

Fig. 7 Tensile force and strength (a) and elastic modulus (b) of roots in different diameter classes. Different lowercase letters indicate significant differences among different diameter classes at $P<0.05$ level. Different uppercase letters indicate significant differences between species at $P<0.05$ level. Bars are standard errors.

3.7 Comparison of root tensile properties and root pullout properties

Under 100 mm/min loading rate, peak root pullout force and root tensile force were positively correlated with root diameter in power functions for *M. sativa* (Fig. 8) and *H. rhamnoides* (Fig. 8b), while root pullout strength and root tensile strength were negatively correlated with root diameter for *M. sativa* (Fig. 8c) and *H. rhamnoides* (Fig. 8d). It can be seen that the peak pullout force and pullout strength as well as the tensile force and tensile strength of the roots are related to the root diameter. Besides, the effect of root diameter may be more effective under 100 mm/min loading rate.

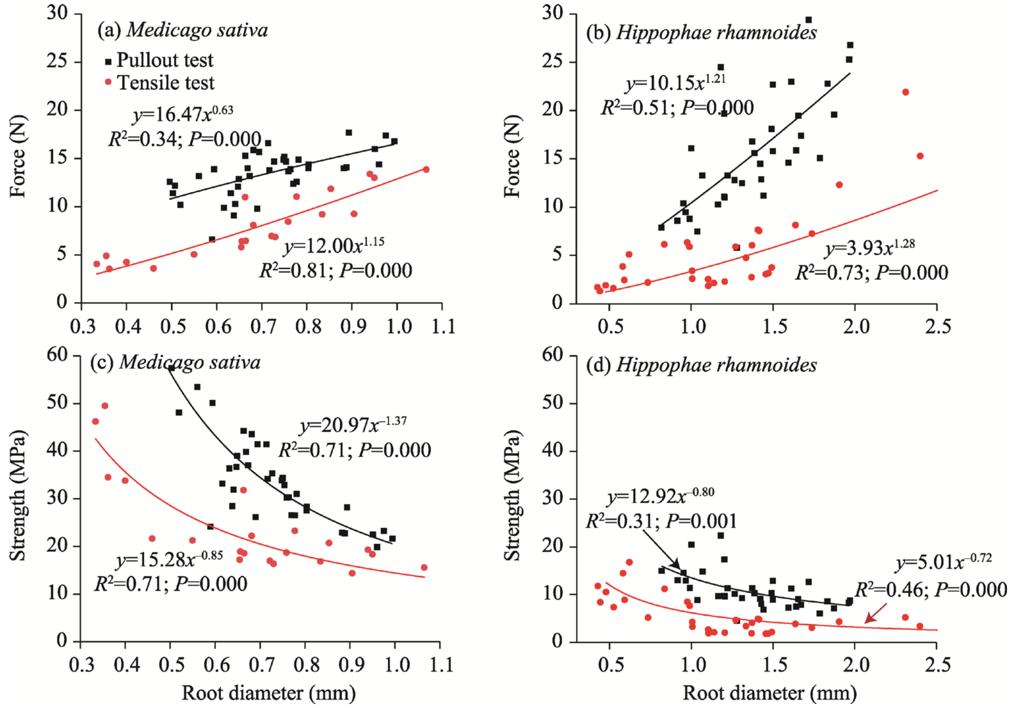

Fig. 8 Correlation of root pullout force and root tensile force with root diameter for *Medicago sativa* (a) and *Hippophae rhamnoides* (b), and correlation of root pullout strength and root tensile strength with root diameter for *Medicago sativa* (c) and *Hippophae rhamnoides* (d)

Mean root pullout strengths of *M. sativa* and *H. rhamnoides* were 35.18 (±1.78) and 10.78 (±0.63) MPa, respectively. Mean root strength obtained from pullout tests was considerably greater than that obtained from tensile tests. This is expected from that the force required to induce failure in pullout tests was considerably higher than that in tensile tests for roots with the same diameter in sandy loam.

3.8 Correlation of root diameter and loading rate with root pullout performance

No significant correlation was observed between loading rate and pullout parameters (Table 2). Correlations between root diameter and parameters varied with species. For *H. rhamnoides*, root diameter was only significantly correlated with peak pullout force and pullout strength. For *M. sativa*, root diameter was correlated with root-soil friction coefficient as well as peak pullout force and pullout strength. Besides, a positive correlation existed between peak root pullout force and fracture root diameter for *H. rhamnoides*. Root displacement was negatively related to fracture root diameter. No significant relationship was observed between pullout performance and fracture root length.

Table 2 Correlation coefficients of root diameter and loading rate with pullout performance of *Medicago sativa* and *Hippophae rhamnoides* roots

Parameter	Root displacement	Peak pullout force	Pullout strength	Root-soil friction coefficient	Pullout energy
Medicago sativa					
Loading rate	–0.042	0.315	0.206	0.379*	0.011
Root diameter	–0.305	0.627**	–0.809**	–0.435**	–0.181
Hippophae rhamnoides					
Loading rate	–0.157	0.162	0.078	0.153	0.005
Root diameter	–0.233	0.718**	–0.544**	0.152	0.282
Fracture root diameter	–0.422*	0.603**	–0.265	0.212	–0.092
Fracture root length	0.212	0.017	0.186	0.164	0.172

Note: *, $P<0.05$ level; **, $P<0.01$ level.

Considering the effect of root diameter, ANCOVA was used to study the effect of different loading rates on root pullout performance. Peak pullout force was significantly different among different loading rates for *M. sativa* (F=4.62, P=0.005) and *H. rhamnoides* (F=2.71, P=0.049), but root pullout strength was not significantly different for *M. sativa* (F=1.98, P=0.120) and *H. rhamnoides* (F=2.13, P=0.102). Besides, root-soil friction coefficient was significantly different for *M. sativa* (F=3.61, P=0.015), but was not significantly different for *H. rhamnoides* (F=2.62, P=0.055).

4 Discussion

4.1 Root failure modes

In this study, all *M. sativa* roots were pulled out, while 72.2% of *H. rhamnoides* roots were broken. Root tensile strength of *H. rhamnoides* was significantly lower than that of *M. sativa*, which mainly resulted from difference of root diameter of the two species as their root tensile forces were not significantly different. This was the main reason that *H. rhamnoides* roots were easier to be broken than *M. sativa* roots. Two root failure modes were observed during root pullout tests in this study, breakage failure, and slippage failure, just like the phenomenon found in other researches (Pollen, 2007; Schwarz et al., 2010a). Generally, roots are in breakage failure when root tensile force is less than the maximum root-soil friction force. On the contrary, roots probably tend to be in slippage failure (Pollen, 2007; Leung et al., 2018). Root pullout force is not only determined by friction between root system and soil, but also determined by root tension

resistance (Osman et al., 2011). Besides, root failure in root tensile tests is likely to be initiated at weak points within roots, which is prone to stress concentration (Hales et al., 2013; Wang et al., 2019). Root tensile strength is the maximum tensile force that root system per unit area can bear before breaking (Genet et al., 2005), and root pullout strength reflects the maximum friction force between root system and soil per unit area of roots (Norris, 2005; Giadrossich et al., 2013). The above reasons could usually result in lower root tensile strength than pullout strength, like the result observed in this study that root pullout force and pullout strength of *M. sativa* and *H. rhamnoides* were greater than root tensile force and tensile strength. Some studies have shown that fine roots are more likely to be broken into segments, while thick roots are easier to be pulled out in pullout tests (Pollen, 2007; Schwarz et al., 2010a), which is not consistent with the results in our study. The reason for the phenomenon may be that root-soil friction is affected by complex factors, like curvature and elasticity of roots, as well as root length and number of root branches (Schwarz et al., 2010a; Cohen et al., 2011; Schwarz et al., 2011).

Mechanical models of root reinforcement, such as Wu-Waldron model (Waldron, 1977; Wu et al., 1979) and root bundle model (Schwarz et al., 2011), involve root tensile force or root pullout force. They are generally measured by root tensile tests and root pullout tests, and probably different even for the same roots. Besides, significant difference in pullout force could exist between slippage roots and breakage roots in pullout tests. To make the root reinforcement models more comprehensive and practical, we considered root pullout force and root pullout strength in the models instead of root tensile force and root tensile strength.

4.2 Effects of root diameter and loading rate on root pullout behavior

Root peak pullout force and strength were relatively less affected by loading rate and depended mainly on root diameter. Negative correlation between root pullout strength and root diameter is consistent with the relationship between root tensile strength and root diameter (Osman et al., 2011). The observed specific relationship that root-soil friction coefficient decreased with root diameter has not been reported. The possible reason is that increase in root diameter causes a change of root surface unevenness when root system grows. *M. sativa* roots had larger diameter and could have smoother surface, which resulted in a decrease in friction coefficient. Presence of nodes or microscopic features on root bark might have a greater effect on root-soil friction coefficient than root diameter. Nevertheless, no such results are currently available, and future studies are needed.

Roots with larger diameter generally have higher cellulose content (Genet et al., 2005) and lower limited root elongation. Roots loosen in faster speed during pullout tests, which is part of the reasons for decrease in displacement with root diameter. Variation of root displacement in pullout tests is also inseparable from soil conditions. For example, Schwarz et al. (2011) showed that root displacement at peak pullout force increased with increasing size of dominant root diameter in a bundle of roots. Relationship between root diameter and root pullout energy was not obvious.

Loading rates affected the failure mode of roots. Roots broke at different distances under different loading rates, while location of root damage was relatively fixed on account of very similar fracture diameter. The maximum peak pullout forces of the two plants was observed at 100 mm/min loading rate. No statistically significant difference in peak pullout force was observed among different loading rates when the effect of root diameter was included, which is similar to previous study (Ji et al., 2018). However, peak pullout force was significantly affected by loading rates when the effect of root diameter was excluded. Except for failure mode and peak pullout force, other pullout parameters, including root pullout strength, root displacement, root-soil friction coefficient, and root pullout energy were not significantly affected by loading rates. Greater values of pullout force, root-soil friction coefficient, and pullout energy were observed under 100 mm/min loading rate in this study. Loading rates that were greater or smaller than 100 mm/min resulted in decreased root pullout force (strength) that could be conservative for estimates of root reinforcement and analysis of slope stability. Based on the above findings, if the

conditions and instruments of root pullout tests are limited, there is no need to deliberately control loading rate in root pullout tests due to its insignificant effect on root pullout properties. In this study, influencing factors such as soil type, soil water content, and root length were fixed, and range of root diameter of the two species was relatively limited. Therefore, effect of loading rate on root pullout performance under other conditions should be deeply analyzed in future research.

5 Conclusions

To explore whether pullout performance of herbaceous plants and shrubs is affected by loading rates, we carried out laboratory pullout tests on the roots of *M. sativa* and *H. rhamnoides*. Results showed that two root failure modes, slippage and breakage, were observed during root pullout tests. Modes were affected by loading rates, as well as mechanical properties of plant roots and root-soil interaction. Root pullout force was significantly related to root diameter. Peak root pullout force was significantly affected by loading rates when the effect of root diameter was included, and vice versa. Except for failure mode and peak pullout force, other pullout parameters, including root pullout strength, root displacement, root-soil friction coefficient, and root pullout energy were not significantly affected by loading rates. For these two species, root pullout strength was greater than root tensile strength. Results suggest that there is no need to deliberately control loading rate in root pullout tests, and root pullout force and pullout strength could be a better parameter for root reinforcement model compared with root tensile force and tensile strength as root pullout force and pullout strength could more realistically reflect the working state of roots in soil.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

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